SEASONAL THERMAL ENERGY STORAGE OF SOLAR ENERGY IN ABANDONED COAL MINES

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Abstract – The use of abandoned coal mines as seasonal thermal energy storage for solar energy is investigated from a technical and economical point of view. This usage is contrasted with using abandoned coal mines as a low temperature heat source for a heat pump, which is the common use in the literature. These two choices are compared for a case study: the city of Genk in Belgium. Genk has 3 mines with a historical combined total production of 175 million ton of coal that were operated until 1988. The underground has been entirely flooded, resulting in an artificial underground water reservoir of 16,7 million m^3. Furthermore, the city of Genk has a population of 65,000 inhabitants and hence, there is a significant heat demand in the proximity of the abandoned coal mines. This study features the comparison of two configurations for exploiting the mines as heat storage or heat source for a swimming pool in Genk, with a yearly heat demand of 2700 MWh. The best configuration depends on the activated underground volume. For this particular case, when activating a stone drift with a diameter of 4.22 m, a stone drift of up to 2 km in length is more suited for thermal energy storage, regenerated by solar energy. If a stone drift of more than 5 km can be activated, the abandoned coal mine is more suitable as a low temperature heat source for a heat pump.

1. INTRODUCTION

Seasonal thermal energy storage (STES) is a crucial technology to increase the share of solar energy within the heating sector. Sensible thermal energy storage is the main mechanism for attaining STES, as opposed to latent and chemical STES which are rarely demonstrated on a large scale (Xu, Wang and Li, 2014). In Belgium, STES is typically attained in an indirect way by using a heat pump, which extracts heat from or injects heat in an aquifer (Vanhoudt et al., 2011) or a borehole heat exchanger (Antonov, 2016) (Žáčeková, Váňa and Cigler, 2014). In Belgium, these systems are typically installed for buildings with a significant cooling demand, for which the ground can deliver the cooling directly during summer and in this way regenerates the ground during summer, such that the heat stored can be used as an interesting source for a geothermal heat pump. This application for shallow geothermal heat and cold benefits from the average temperature of 10°C of the shallow underground in Belgium. The aquifer or borehole heat exchangers act subsequently as a “cold storage”.

This paper looks at another alternative in the underground for STES, namely abandoned mines. Worldwide, there have been a few applications of using water from abandoned mines, as summarized in Table 1. From this table, it is clear that the mines are mostly used directly for

Table 1: Overview of minewater projects based on (Ramos, Breede and Falcone, 2015) (Watzlaf and Ackman, 2006) (Verhoeven et al., 2014)

Country	Town	Extract depth (m)	Extract temp. (°C)	Inject depth (m)	Mass flow rate (m³/h)	Supply temp. heating/cooling (°C)	Thermal power (kW)	End-use (size in m²)
Canada	Springhill	140	13-25	30 m	14.4		11 heat pumps	Industry (14000)
Germany	Ehrenfriedersdorf	110		110			138	Mining
Germany	Freiburg (castle)	60	10.2		10.8	42 / 19	130	Castle
Germany	Freiburg (university	216	18	216		55 / -	260	University
Germany	Marienberg	105	12.4	105	124–2000		310	Recreation
Germany	Wettelrode	283	12–13	163	90–150	50 / -	47	Mining (400)
Netherlands	Heerlen	700 (heat)	27–32	350	0-230	45 / -		Multiple
		250 (cool)	16	350	0-230	- / 16		(500000)
Russia	Novoshakhtinsk	50-150	12–13			95 / -	40000	Multiple
Spain	Asturias		17–23			50 / 7	4600	Multiple (85000)
UK	Shettleston	100	12	Below water table		55 / -	2 heat pumps	Residential
UK	Lumphinnans	170	14.5	Strata layer		45-53 / -	Heat pump	Residential
USA	Kingston		16		20.5	50 / -		Recreation (1580)
USA	Park Hills, MO	120	14	122	17	22 / 24	113	Municipality (753)
USA	Scranton, PA	122	14			- / 13		University

cooling or as a source for a heat pump, i.e. similar to the use of the aquifer or borehole heat exchanger in Belgium. In Table 1, the highest temperatures are extracted from a mine in Heerlen, The Netherlands (Verhoeven et al., 2014) (Ferket, Laenen and Van Tongeren, 2011), which is only 40 km away from Genk, Belgium. Genk has 3 mines with a historical combined total production of 175 million ton of coal that were operated until 1988. Modelling of water ingress after closure of the mines indicates that the underground has been entirely flooded by now, resulting in an artificial underground water reservoir of 16.7 million m^3. The deepest mine corridors, at a depth of 1000 meter, each have a volume between 100 to 500 thousand m^3, surrounded by rock at a temperature of about 40 to 45°C. Furthermore, the city of Genk has a population of 65,000 inhabitants and hence, there is a significant heat demand in the proximity of the abandoned coal mines.

The water temperature in the deepest mine corridors makes these corridors an interesting option for “hot storage”. This matches the low-temperature heat demand in Genk well. Given the low potential of waste heat from industry nearby, there is little competition nearby from other heat sources when looking at district heating. As can be seen in Table 1, the mine water is usually used as a low temperature heat source, but not as a thermal energy storage. The exception to this is Heerlen, where one part of the mine is used as a cold storage and another part as a heat storage.

In this paper, we investigate the use of the abandoned coal mine as a heat storage or heat source. Two system configurations are considered in this study. In the first, the mine is merely a heat source and there is no active recharging of the mine. In the second configuration, solar thermal panels are added to recharge the mine. This paper presents the comparison of these two system configurations in a case study for Genk, with a variable size of the mine corridors that is activated.

2. METHODOLOGY

This Methodology section is organised as follows. In order to compare the two system configurations, a case study in Genk, Belgium, is chosen and described. Next, a model for a horizontal mine corridor, called a stone drift, is presented and verified with respect to a finite element model. Finally, the two system configurations are discussed.

2.1 Case study description

From an overview of large buildings in Genk, the public swimming pool ‘SportinGenk’ was selected as an interesting case study to start exploring the thermal potential of the abandoned coal mines. As shown in Figure 1, the swimming pool (S in Figure 1) is only about 1.2 km away from the central mine shaft of the abandoned coal mine of Winterslag (M in Figure 1). The mine of Winterslag has an open space of about 4.8 million m^3, part of which is located closely to the swimming pool. Large parts of the mine are more than 700 m deep, at a temperature of more than 30°C. This makes it a very interesting heat source for a swimming pool.

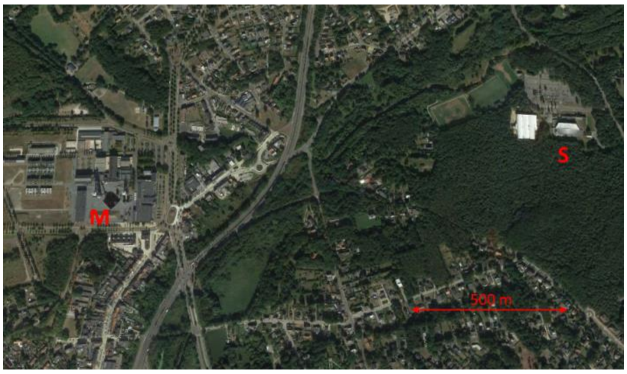

Figure 1: Top view of swimming pool (S) and abandoned mine shaft (M). Image from Google Earth.

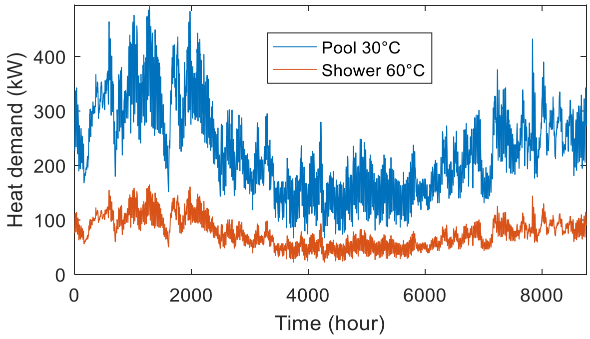

Figure 2: Assumed heat demand profile for the swimming pool, split up in the low temperature heat demand for the pool and high temperature heat demand for the showers.

The swimming pool of Genk is is equipped with a combined heat and power (CHP) plant of 300 kW_{el} and 450 kW_{th}. On top of this there are two backup condensing gas boilers of 450 kW_{th} each. The swimming pool and changing rooms are equipped with floor heating. Given this floor heating and the large heat demand for refreshing the swimming pool water at around 30°C, a large part of the heat demand is at a low temperature. Higher supply temperatures are needed for the showers, as well as for the ventilation of the other rooms, specifically the cafeteria, judo room, fitness room and other areas. We estimate the yearly heat demand of the swimming pool to be 2700 MWh. Based on (Schrier, 2001), we determine that 25% of the heat demand is at a high supply temperature of 60°C and 75% of the heat demand is at a low supply temperature of 35°C. Starting from normalized heat demand measurements for another pool, the heat demand profiles for the swimming pool of Genk are determined in Figure 2.

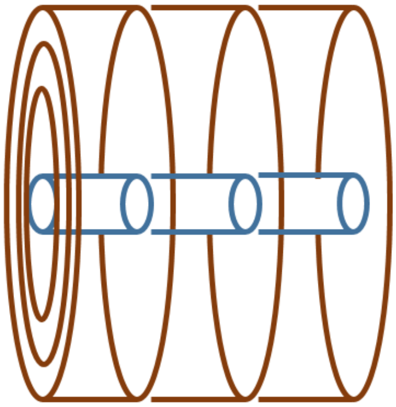

Figure 3: Discretization of a stone drift and the soil around the stone drift

2.2 Stone drift model

The horizontal corridors of the mine (called stone drift throughout this paper) are modelled in Modelica to allow for efficient system simulations. Figure 3 shows conceptually how the stone drift and the soil around it is modelled in Modelica. The water in the stone drift and the soil around it are discretized in the longitudinal direction. On top of that, the soil around the stone drift is discretized in the radial direction, with the discretization scheme of Eskilson (Eskilson, 1987). The water in the stone drift is modelled as mixing volumes and hence, plug flow is not taken into account. Finally, the geothermal heat flux is not modelled since it has a low thermal power and is hard to represent in the cylindrical model.

The Modelica model is verified with respect to a finite element model implemented in TOUGH2 (Pruess, Oldenburg and Moridis, 1999). Figure 4 describes the set-up of the verification study. A stone drift initially at 25°C receives from one side colder water at 10°C at a mass flow rate of 5.6 kg/s. Figure 4 summarizes all parameters of the case study, except the convective heat transfer coefficient, which has a constant value of 2 W/m²K.

Both the TOUGH2 model and the Modelica model are

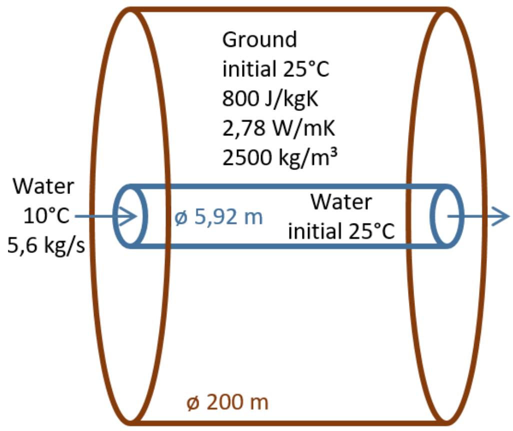

Figure 4: Verifciation case study of the stone drift model

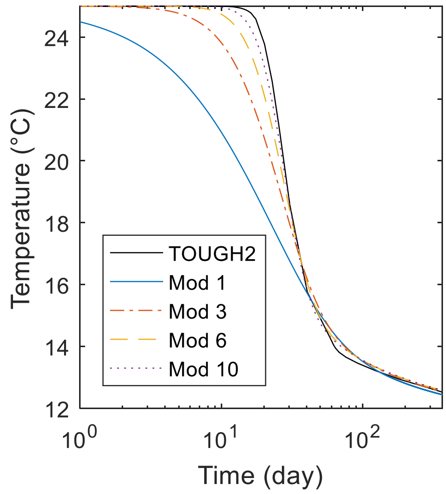

Figure 5: Verification of the stone drift Modelica model (using 1, 3, 6 or 10 longitudinal discretizations) with respect to the TOUGH2 model: temperature of the water exiting the stone drift after injecting water at 10°C

simulated for 1 year. The temperature of the water exiting the stone drift is plotted as a function of time in Figure 5. Four variations of the Modelica model are tested, using different longitudinal discretizations, respectively 1, 3, 6 and 10 discretizations. All four variations appear well equipped to estimate the long term (>100 days) thermal behaviour of the stone drift. Over a full year, the mean absolute error (MAE) is 0.43°C, 0.22°C, 0.15°C and 0.10°C for 1, 3, 6 and 10 discretizations respectively. However on the short term, the Modelica model without longitudinal discretization (Mod 1) is totally unsuitable for representing the stone drift. Over the first month, the MAE is namely 3.74°C, 1.61°C, 0.74°C and 0.29°C for 1, 3, 6 and 10 discretizations respectively. Hence, with 10 longitudinal discretizations (Mod 10), the Modelica model differs less than 0.5°C from the TOUGH2 model output. For the sake of completeness, also 3 (Mod 3) and 6 (Mod 6) longitudinal discretizations are shown in Figure 5. Throughout the rest of this work, the Mod 10 model is used in order to attain sufficient accuracy.

2.3 Heating system lay-out

As mentioned in the introduction, two system configurations are studied in this paper. Figure 6 schematically illustrates these configurations. For the sake of simplicity we assume that one long stone drift is activated, so we don't consider multiple pathways of the water as is usually the case in abandoned coal mines, see (Ferket, Laenen and Van Tongeren, 2011). This stone drift is assumed to be at a depth of 735 meter and at a starting temperature of 32.5°C. The stone drift has a diameter of 4.22 meter. The soil around the stone drift has a thermal conductivity of 2.3 W/mK, a density of 1280 kg/m³ and a specific heat capacity of 800 J/kgK. The pump extracts the water from the stone drift at a mass flow rate of 108 m³/h and provides this mass flow

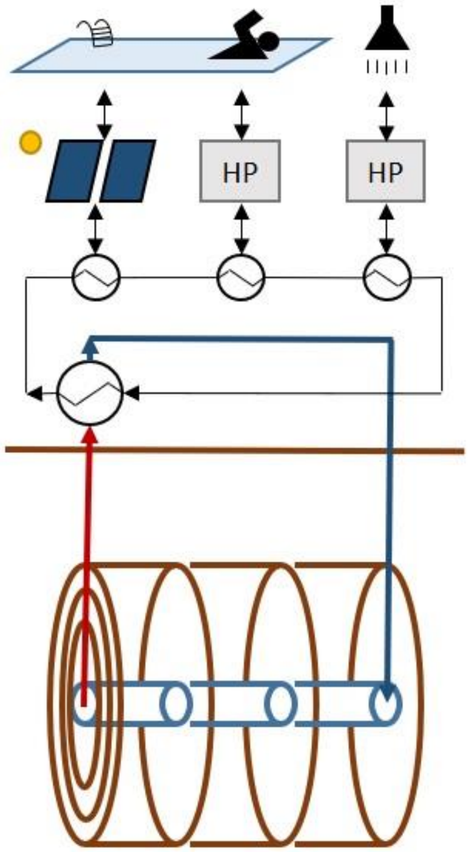

Figure 6: Schematic overview of the possible system configurations. The heat pump (HP) always secures sufficient heat supply. A solar collector field can be added for preheating the water from the mine and regeneration in summer.

rate throughout the whole year. Since the pressure drop calculations can be quite challenging for this system, we neglect the expenses for pumping in this study. Both configurations studied use this pump continuously throughout the year, so it will not make a difference when comparing the two configurations. The length of the stone drift which is hydraulically activated, is varied in this study between 1 and 10 km.

The first configuration is called ‘Heat Pump’, abbreviated to ‘HP’. In this configuration, the stone drift is solely used as a source for the heat pumps (HP in Figure 6). Two drillings are made in a stone drift (blue and red arrows). The water within the stone drift is circulated towards a heat exchanger. If the temperature is sufficient to supply the heat demand of the pool directly, this option is used first. After this, two heat pumps are active. One for supplying the pool with heat at a supply temperature of 35°C and one for supplying the showers with a supply temperature of 60°C.

The heat pump is modelled using the ‘Carnot_TCon’ model of the ‘Buildings library’ (Wetter et al., 2014) in Modelica. This model supplies a constant supply water temperature. The coefficient of performance (COP) is determined based on Carnot and normalized to a nominal COP value at design temperature levels. The nominal value of the COP is based on (Bettgenhäuser et al., 2013):

$$COP = a \cdot \frac{T_{supply}}{T_{supply} - T_{source} + b}$$

with T_{supply} the nominal supply water temperature and T_{source} the nominal source temperature, which is assumed 25°C in this study. The parameters a and b are taken for a ground coupled heat pump of (Bettgenhäuser et al., 2013), namely a is 0.5 and b is 10. The heat pumps are sized in order to deliver the peak heat demand based on Figure 2.

The second configuration is called ‘Solar’, abbreviated to ‘Sol’. In this configuration, a solar thermal collector field is installed. For modelling this thermal collector, the ASHRAE93 model is used from the ‘Buildings library’ (Wetter et al., 2014) with the parameters of the FP - Therma-Lite, HS-20, a glazed flat plate collector. We assume 10,000 m² of these flat plate collectors in this study, with a southward orientation and a tilt of 30°C. These solar collectors preheat the water that is directed towards the heat pumps. If the solar collectors are warmer than the water coming out of the mine, a secondary circuit pump is activated and the water that exchanged already heat with the mine water is further heated by solar energy. The heat pumps can then deliver the last temperature lift in order to supply the heat demand at the desired supply water temperature. If the water is still at a higher temperature than the mine water after heat supply to the heat pump, the solar collectors are heating up the mine water too.

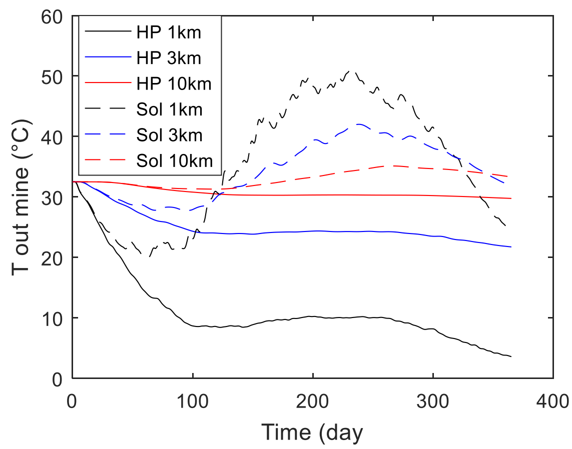

Figure 7: Temperature of the water coming out of the mine, throughout the year for a stone drift length of 1, 3 or 10 km. In the heat pump (HP) configuration, this temperature substantially drops. In the solar (Sol) configuration, the temperature rises throughout the summer and hence, heat is stored in the mine.

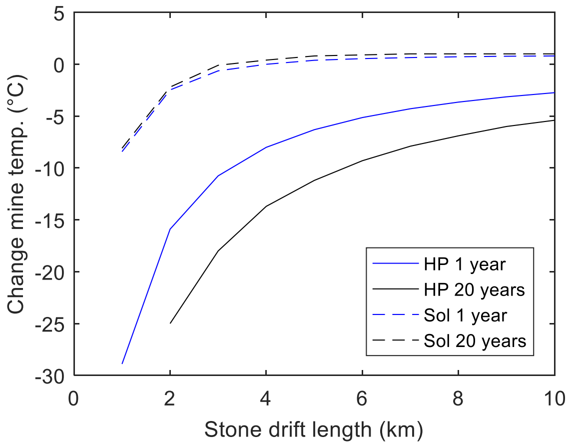

Figure 8: Change in temperature of the water exiting the mine after 1 and 20 years.

To wrap up, the HP configuration can be seen as the heat extraction scenario. In this case, we solely extract heat from the mine. In the Sol configuration, flat plate collectors are installed to supply part of the heating in summer but also regenerate (heat) the mine for later use. In this case, the stone drift acts as a storage. For both configurations, the activated stone drift length will be varied in order to compare both configurations.

3. RESULTS

Both HP and Sol configurations are simulated for one year. Figure 7 shows the temperature exiting the mine throughout a year for multiple stone drift lengths. In case of a 1 km stone drift, solely extracting heat ('HP 1km' in Figure 7) is clearly not sustainable. The temperature of the water in the stone drift drops to 5°C after 1 year, which means a temperature decrease of 28°C in one year (the first year). When the stone drift is longer, this configuration gets more sustainable, with for a 10 km stone drift a temperature decrease of only 2.5°C in one year (the first year). In the case of a long stone drift length, a large horizontal surface area is activated. In this case, the geothermal heat flux can become influential. However, this is hard to represent in this cylindrical model and will be considered in future work.

When the solar collectors are added, the temperature throughout the year follows a significantly different path. The heat pumps still lower the stone drift temperature in the beginning of the year (in winter), but the stone drift is substantially heated throughout summer. The stone drift acts as a thermal energy storage: the temperature of the stone drift clearly rises and this is not directly lost due to heat losses. The amplitude of the temperature variation is larger the shorter the stone drift is.

Figure 8 shows the difference in stone drift water temperature after 1 year and 20 years of operation. For the HP configuration, the temperature quickly drops after 1 year of operation. Comparing this temperature drop to the one after 20 years, we observe that almost half of the temperature drop happens within the first year. After this first year, the decline per year is more steadily. The HP configuration with 1 km of stone drift reached 0°C after 1 year and 1 month, after which the simulation was terminated. With a 2 km stone drift, the heat pump was able to run for 20 years while the water in the stone drift reached a temperature of 7.5°C. For longer stone drifts, the temperature drop decreases, resulting in higher mine temperatures and hence higher heat pump efficiency.

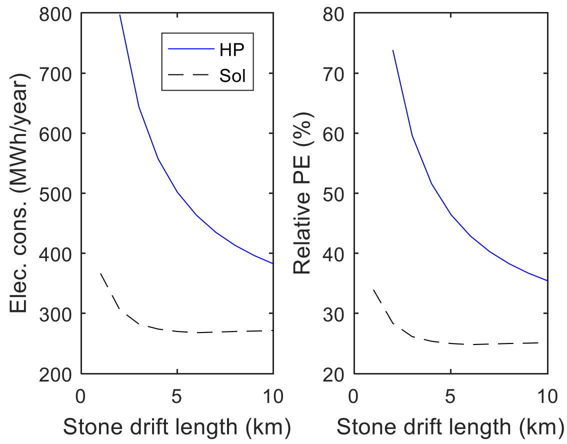

Figure 9: Yearly electricity consumption of the heat pumps (left), also expressed in relative primary energy (PE) use (right) compared to 2700 MWh supplied with a gas boiler.

For the Sol configuration, the system is in equilibrium: after 1 year, the same temperature difference is reached as after 20 years (Figure 8). The same stone drift temperature profile is repeated each year. The temperature drop for the Sol case remains limited for all stone drift lengths and reaches zero at a stone drift length of 3 km, after which a slight temperature increase occurs.

The difference in stone drift water temperature between the HP and Sol configuration gets smaller as the stone drift length increases (Figure 8). This has an effect on the yearly electricity consumption of the heat pumps, which converges for longer stone drift lengths, as Figure 9 (left) shows. The yearly consumption is also expressed in terms of relative primary energy use, compared to the use of a gas boiler (Figure 9 (right)). To this aim, the electricity consumption is translated to primary energy by using a factor of 2.5. This primary energy consumption is compared to the case where the full 2700 MWh of heat demand would be supplied by a gas boiler. This metric is easier to interpret. For short stone drift lengths and a HP configuration, the primary energy savings are rather limited: about 25%. The heat pump configuration clearly needs a significant stone drift length in order to deliver large primary energy savings. The Sol configuration on the other hand, delivers substantial primary energy savings (up to 75%), even for shorter stone drift lengths. Notice in the Sol configuration how the electricity

Table 2: Optimistic and pessimistic price assumptions for the investment, running costs and interest rate. Collector price based on (Nielsen and Battisti, 2012) Connecting pipe price based on (Frederiksen and Werner, 2013). Other data from personal communication with practitioners.

	Price per unit (EUR)		Units
	Optimistic	Pessimistic	needed
Drillings towards the mine	400k/drilling	600k/drilling	2 drillings
Connecting pipe	300/m	600/m	1500 m
Heat pump	200/kW	200/kW	650 kW
Flat plate solar collectors	150/m²	225/m²	10000 m²
Electricity	150/MWh	180/MWh	-
Interest rate	3%	7%	-

demand (Figure 9) stabilizes at a stone drift length of 3 km. From this point onwards, it's clearly not needed anymore to activate a longer stone drift. The electricity use even slightly goes up for longer stone drift lengths (Figure 9), which indicates a higher heat loss to the surrounding rock. For this case, the optimal stone drift length is 5 km. But as one can notice, this is a weak optimum, as a stone drift length between 3 and 7 km almost performs equally.

Finally, the choice between the heat pump and Sol configuration will be based mainly on cost. Table 2 shows the considered ranges for major cost components. We assume that the system runs for 20 years except for the connecting pipe and drillings, for which we take an economic lifetime of 40 years. The length of the connecting pipe is 1500 m, based on Figure 1. Hence, we assume that the multiple stone drift lengths can be activated with a same distance covered above ground. In other words, for the longer stone drift lengths, we assume that parallel paths can be activated.

Based on Table 2 and the electricity consumption data in Figure 9 (left), the cost for supplying 2700 MWh per year is shown in Figure 10. From this figure, it appears that the Sol configuration shows a very large spread in cost. This is mainly attributed to the cost of the flat plate solar collectors. When these show a low cost and the interest rate is favourable, then the Sol configuration can economically compete with the HP configuration for a stone drift length of up to 5 km. For larger stone drift lengths, the HP configuration clearly outperforms the Sol configuration, for the whole range of cost assumptions.

One can interpret Figure 10 also in a more abstract way. For this particular case, up to 2 km stone drift length, the stone drift is more favourable as an energy storage. Starting from 4 km stone drift length, the stone drift is more favourable as a heat source. Off course, these values are highly case dependent, as they depend on technical and economical parameters.

Finally, Figure 10 compares both configurations to the typical range of the natural gas price for Belgian

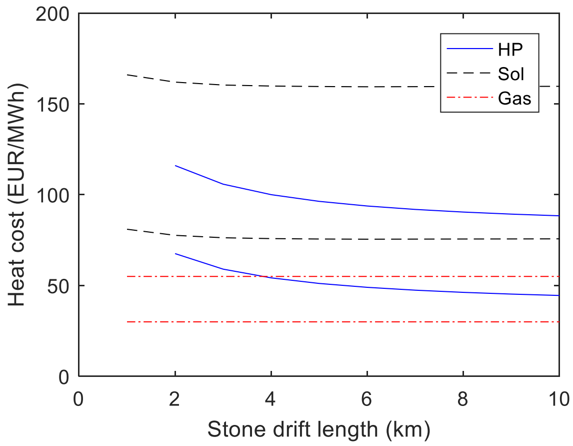

Figure 10: Cost ranges for supplying 1 MWh of heat for the heat pump and solar configuration. This is compared to a typical price for natural gas (Gas). The top and bottom lines are the pessimistic and optimistic cost estimates, respectively;

consumers with a yearly demand in the range of 2700 MWh. These days, the natural gas price is more towards the lower end of the range, but this price is known to fluctuate strongly over the years. When comparing both the HP and Sol configuration to the natural gas price, it is clear that both configurations are not very competitive with natural gas in an economic sense. Only the HP configuration in favourable conditions and long activated stone drift lengths, can compete directly to a natural gas boiler. Hence, the choice for these configurations will be driven more by environmental reasons, namely the reduction in primary energy use as shown in Figure 9.

4. CONCLUSIONS

This paper compares the use of abandoned coal mines as a thermal energy storage for solar energy ('solar') and as a low temperature heat source for a heat pump ('heat pump'). To this aim, a thermal model of a mine corridor (or stone drift) was developed in Modelica. The aforementioned comparison was performed for a swimming pool in Genk. In the solar configuration, the temperature of the stone drift is stable already from year one onwards. Substantial primary energy savings of up to 75% can be achieved with this configuration. Furthermore, it is economically competitive with respect to the heat pump configuration for shorter stone drift lengths (up to 2 km) in this case study. The heat pump configuration could be attained for 20 years as soon as the stone drift length was longer than 2 km. However significant temperature drops (up to 25°C after 20 years) are observed in the stone drift for small lengths. For a 2 km stone drift length, the primary energy savings are rather limited (around 25%). The heat pump configuration needs a longer stone drift length to show interesting primary energy savings and to compete with the solar configuration. For a stone drift length larger than 5 km in this case study, the heat pump configuration is on average cheaper than the best case solar configuration. Hence the choice between both configurations depends on the ratio between heat demand and available stone drift volume.

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